Computerized Detection of Arterial Oxygen Desaturations in an Intensive Care Unit

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ABSTRACT

Automatic detection of arterial oxygen desaturations was investigated by collecting pulse oximeter saturation data through an MIB. Two algorithms, one based on a threshold principle and the other based on moving median calculations, performed the detection. The median algorithm detected fewer "unimportant" events than did the threshold algorithm, but also did not detect some "important" events that the threshold algorithm detected. Successful detection algorithms will likely need to incorporate into their decision-making other patient information in addition to saturation. A proposed recording algorithm is described.

INTRODUCTION

Many types of bedside devices are in routine use in Intensive Care Units (ICUs) today. Pulse oximeters, intravenous fluid pumps, electrocardiogram monitors, mechanical ventilators, and other devices generate important information used by physicians, nurses, and therapists for the care and treatment of critically ill patients. Most of these devices are currently equipped with microprocessors that perform signal conditioning and processing and serial output ports that allow connection to a computer.

Connection of these devices to computers has the potential to enable timely, automatic, and accurate recording of large quantities of physiological data previously unavailable to the clinician. Others have observed, however, that more patient data does not automatically ensure better patient care [1-5]. If the advantages of automatic computerized monitoring are to be realized, prudent data selection methods must be developed.

One facet of the data selection process is identification of "important" clinical events. Computerized event detection of a pulse oximeter's arterial oxygen saturation (SpO_2) signal is the subject of this research. Pulse oximeters have been described as "arguably the most significant technological advance ever made in monitoring the well-being and safety of patients during anesthesia, recovery, and critical care" [6]. They noninvasively and continuously monitor and display a patient's SpO_2 and are routinely used in Intensive Care Units.

MATERIALS AND METHODS

The research described was performed in the 12-bed Shock/Trauma/Respiratory Intensive Care Unit (STRICU) of LDS Hospital in Salt Lake City, Utah. A Medical Information Bus (MIB) has been operational at LDS Hospital for four years [7-10]. The key components of the LDS Hospital MIB are Device Communication Controllers (DCCs), Master Communications Controllers (MCCs), and Charles River Data Systems minicomputers. Each bedside device utilizing the MIB is connected to a DCC. The DCC converts bedside device outputs into a standard MIB protocol. The device data are then transmitted to the MCC. There is one MCC in each of the units that utilize the MIB. The MCC processes the device data and relays them to the unit's minicomputer. The minicomputer acts as a preprocessor and multiplexer before relaying data on to the hospital's Health Evaluation through Logical Processing (HELP) clinical information system, which is based on multiple Tandem computers [11].

The STRICU is a level 1 regional trauma referral center that employs four attending MD intensivists. It treats critically ill trauma, respiratory, multisystem organ failure, and postoperative liver transplantation patients. The unit provides treatment for one to two patients per registered nurse and has 24-hour physician coverage.

The oximetry module of the DCC software, written in C and assembly language, was designed to obtain one arterial oxygen saturation value from an Ohmeda Biox 3700 pulse oximeter every 30 seconds. Two event detection algorithms were then programmed in the DCC software.

One detection algorithm operated on a threshold principle; i.e., every minute, the DCC queried the oximeter for the "low saturation" limit that had been set on the oximeter by a nurse. Whenever the saturation read by the DCC dropped below this limit, the DCC triggered an alarm.

The second detection algorithm was based on the calculation of two moving medians. Both moving medians were calculated every 30 seconds as a new saturation value was received. One moving median was calculated from the most recent 6 minutes of saturation data while the other moving median was calculated from the most recent 30 minutes of data. The algorithm detected events in two ways. Firstly, if the current 6-minute median was sufficiently lower than the current 30-minute median, an alarm was triggered; a drop greater than 5% SpO_2 triggered the alarm if the 30-minute median was 94% or above, a drop greater than 3% triggered it if the median was 93%, a drop greater than 2% if the median was 92%, a drop greater than 1% if the median was 90% or 91%, a drop greater than 2% if the median was between 80% and 89%, and a drop greater than 1% if the median was below 80%. This mode of detection was designed to detect short-term deviations from a long-term trend in saturation. Secondly, if the current 30-minute median was more than 2% SpO_2 lower than the 30-minute median calculated 25 minutes before, the alarm was triggered. Further details of the algorithms are presented in [12]. The specifics of the algorithms were arrived at by reviewing saturation data with physicians, nurses, and respiratory therapists.

The detection algorithms triggered an audible alarm in the DCC, which was attached to the oximeter at the patient's bedside. When an alarm sounded, the attending nurse or respiratory therapist was requested to reset the alarm by pressing a button on the face of the DCC and record the time and his or her observations on a paper checklist kept by the side of the bed. Two of the checklist questions are presented below.

1. On a scale of 0 to 5, **0 being totally unimportant and 5 being an immediate threat to life**, how clinically important did you consider this desaturation to be?

2. What action(s) did you take?

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No action
Diagnostic actions:
  waited and watched
  checked probe placement/probe
    condition and corrected
    any malfunction
  checked operation of O2 delivery
    system and corrected any
    malfunction
  ordered ABG
  notified physician
  other (specify)
Therapeutic actions:
  increased FiO2
  turned patient
  changed O2 delivery
  suctioned patient
  sedated patient
  other (specify)
```

The algorithms were run on 53 randomly selected STRICU patients for a total of 1600.0 hours (an average of 30.2 hours per patient) between August, 1991 and October, 1991.

RESULTS

The DCC alarms sounded 1419 times (an average of 0.89 times per hour). Alarms were grouped together into "events". Consecutive alarms were considered to belong to the same "event" if the time between one alarm being turned off and the next alarm sounding was less than 5 minutes. Grouping the alarms produced 888 "events". The median algorithm detected 380 "events" and the threshold algorithm detected 785. There were 277 "events" that were detected by both algorithms. Checklist answers were then hand-correlated with "events". Question 1 was answered 593 times (66.8% compliance) and question 2 was answered 579 times (65.2% compliance). The performance of the detection algorithms with respect to questions 1 and 2 are presented in Tables 1 and 2 respectively.

Table 1. Events detected by the two detection algorithms, grouped by the importance ratings given in checklist question 1. Each percentage is the percentage of the total number of ratings recorded for that algorithm, e.g., 3 events rated "5" represented 1.2% of the total number of ratings recorded for median algorithm events.

Events Rated As:	Frequency	
	Median Algorithm (250 ratings)	Threshold Algorithm (543 ratings)
immediate threat to life		
5's:	3 (1.2%)	4 (0.7%)
4's:	13 (5.2%)	26 (4.8%)
3's:	31 (12.4%)	49 (9.0%)
2's:	23 (9.2%)	51 (9.4%)
1's:	63 (25.2%)	141 (26.0%)
0's:	117 (46.8%)	272 (50.1%)
totally unimportant		

Table 2. The responses to events detected by the median and threshold algorithms. Each percentage is the percentage of the total number of actions taken in response to events detected by the algorithm, e.g., 52 "no action" responses corresponded to 15.0% of the total number of responses to events detected by the median algorithm.

Action	Frequency	
	Median Algorithm (347 actions)	Threshold Algorithm (741 actions)
No Action	52 (15.0%)	108 (14.6%)
Diagnostic actions:		
waited and watched	30 (8.6%)	75 (10.1%)
checked probe placement/ probe condition and corrected any malfunction	132 (38.0%)	262 (35.4%)
checked operation of O_2 delivery system and corrected any malfunction	31 (8.9%)	59 (8.0%)
ordered ABG	10 (2.9%)	16 (2.2%)
notified physician	4 (1.2%)	10 (1.3%)
Therapeutic actions:		
increased FiO_2	28 (8.1%)	65 (8.8%)
turned patient	7 (2.0%)	16 (2.2%)
changed O_2 delivery	5 (1.4%)	10 (1.3%)
suctioned patient	25 (7.2%)	64 (8.6%)
sedated patient	7 (2.0%)	18 (2.4%)
Other		
therapeutic	16 (4.6%)	35 (4.7%)
non-therapeutic	0 (0.0%)	3 (0.4%)

DISCUSSION

Algorithm Performance Evaluation

An importance rating of 0 or 1 in checklist question 1 indicated events of relatively little clinical importance. Responses of "no action", "waited and watched", "checked probe" or "checked O_2 delivery system" in checklist question 2 also generally indicated events of relatively little clinical importance. (A few cases were found, however, in which nurses responded to events rated as "4" with "checked probe", "checked O_2 delivery", and/or "waited and watched" and no other actions.) Based on these criteria, the median algorithm detected far fewer clinically unimportant events than did the threshold algorithm. The median algorithm detected only 180 events rated 0 or 1 while the threshold algorithm detected 413. Also, events detected by the median algorithm met with 245 responses of "no action", "waited and watched", "checked probe", or "checked O2 delivery", compared with 504 events detected by the threshold algorithm.

A serious liability of the median algorithm, however, was that it also did *not* detect 14 events detected by the threshold algorithm that were rated as 4 or 5; i.e., even though the median algorithm detected fewer *unimportant* events, it also detected fewer *important* events. Overall, an unimpressive 76.1% of the question #1 responses to threshold algorithm events and 72.0% of the responses to median algorithm events were 0's or 1's. Additionally, 68.1% of the question #2 responses to threshold events and 70.5% of the responses to median events were "no action", "waited and watched", "checked probe" or "checked O2 delivery system".

Problems in Reliable Event Detection

Simply "tuning" the algorithms (e.g., allowing 8% drops in the SpO_2 instead of 5% drops before alarming or calculating medians over a different time interval) will unfortunately not guarantee reliable algorithms because other significant problems remain. One problem confronted in attempting more reliable detection of only clinically important events concerns data obtained from the oximeter. Figure 3, for instance, illustrates a desaturation that the nurse attributed to "probe problems" (probe off patient or poor quality signal), yet the oximeter transmitted no alarm messages to the DCC. Oximeter companies are currently attempting to develop new probes and signal processing methods to assure reliable signals under such adverse conditions as patient motion and poor perfusion. Such development must continue in order to assure the type of clean, artifact free signal that is essential to reliable event detection.

Even more problematic for a computerized detection system, however, are desaturations that are real, physiological, desaturations that for one reason or another are of no concern to the clinicians (e.g., desaturations that might occur while turning or suctioning the patient or while the patient is coughing). The threshold algorithm was especially sensitive to these events. Many such events were transient enough in nature that the median algorithm did not detect them. However, Figure 4 illustrates one case in which the median algorithm *did* detect a relatively unimportant event.

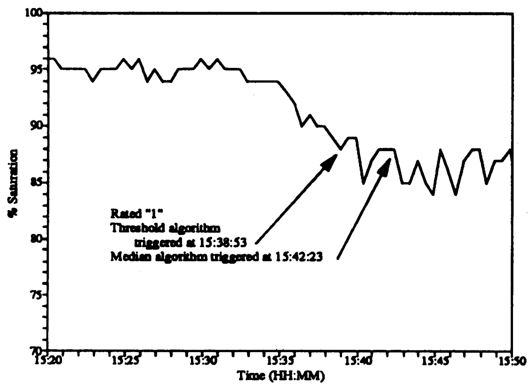

Figure 3. An example of an unimportant desaturation that might appear to be important. The nurse attributed the event to incorrect probe operation and the patient was turned. The recorded data did not show any oximeter alarm messages, however.

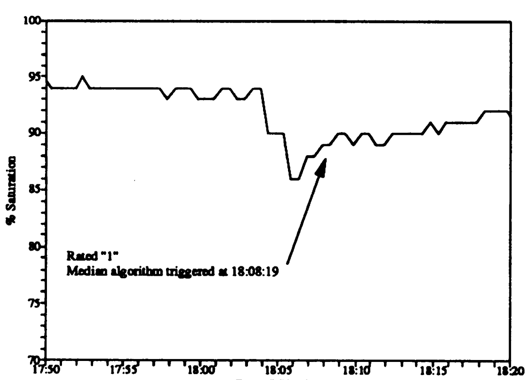

Figure 4. A "unimportant" desaturation detected by the median algorithm. The nurse was suctioning the patient, considered this a "1" in clinical importance on a scale of "0" to "5", and took no action.

A matter for discussion, however, is how these "real" yet "unimportant" events should be dealt with from a recording standpoint. In rating the events "unimportant", the nurses were most likely expressing that they would not need to be alerted to such events; whether or not the events should be recorded in a database is a different question.

Also difficult are events that are clinically important, even though the saturation signal might not indicate it. Figure 5 illustrates this case.

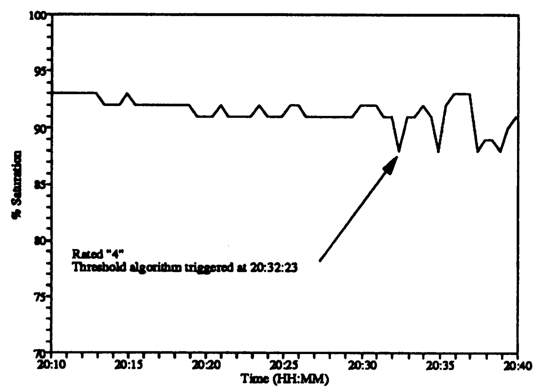

Figure 5. An important desaturation (the nurse rated the event a "4" and increased the FiO_2) that might appear unimportant. The saturation *did* fall to 88%, which is where the oximeter alarm limit had been set, but other cases exhibited more pronounced decreases at similar saturation levels and the nurses/therapists demonstrated less concern.

The "0 to 5" clinical importance scale undoubtedly introduced subjectivity into the study. For instance, one nurse's concept of the importance of a "4" relative to a "3" may have been different from another nurse's. Nevertheless, we felt that the "0 to 5" scale would be a good, although somewhat subjective, parameter to begin investigation of the clinical importance issue.

A more serious type of subjectivity in the study, however, concerned the nurses' and therapists' perceptions of "importance". We could not be sure that, when faced with similar desaturation events, nurses and therapists would respond similarly.

The possible variability in nurses' and therapists' responses and the similarity in appearance of some events rated "important" and other events rated "unimportant" highlight the need for clinicians and medical informaticists to gain a more thorough understanding of the factors in addition to the saturation signal that contribute to the clinical importance of a desaturation. For instance, FiO_2 level, patient temperature and perfusion, and hemodynamic state were among the factors listed by clinicians at LDS Hospital as affecting clinical importance of a desaturation [12]. The relationships between factors such as these, SpO_2 level, and clinical importance need to be investigated and defined before effective computerized event detection is possible. It appears very likely that other patient information in addition to the saturation signal will have to be incorporated into a successful computerized event detection algorithm.

Conclusions and Recommendations

While work continues on improving the reliability of the pulse oximeter's signal and defining clinical importance as it pertains to that signal, we advocate the use of automatic recording algorithms similar to those recommended in [10], i.e., algorithms that use medians to remove obviously spurious saturation readings. The median algorithms may also be designed to identify and record *potentially* important events and make the information available to clinicians, who may then make the determinations regarding the events' importance. At LDS Hospital, we have proposed a system that calculates a 15-minute median each quarter-hour and records it in the patient database. In addition, every 5 minutes, a 5-minute median is calculated. If this 5-minute median differs by more than 4% SpO_2 from the median last recorded in the database, this data will also be recorded. An example of data recording using this algorithm is shown in Figure 6.

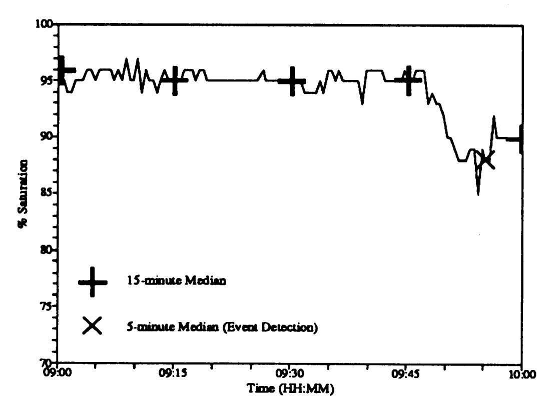

Figure 6. An example of the recording system under test at LDS Hospital.

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